Computational modelling and experimental investigation of the bond behaviour between concrete and braided fibre ropes

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Abstract

Achieving a good bond between fibre and concrete is vitally important. This paper describes an initial investigation of the bond behaviour between concrete and braided fibre ropes as a substitute for steel reinforcing bars. Experiments were performed to determine the bond behaviour at ambient conditions. An equivalent 7mm diameter Siltex© pre-stressed carbon fibre ropes embedded in 6 samples of 150mm by 200mm C40 concrete cylinders were used for pull-out tests according to ACI 440.3R-04. Due to the lack of rope surface deformation, an average bond stress of 4.17MPa was achieved, approximately 36% of bond strength of 7mm steel reinforced bar (as defined by CEB-FIP Model Code and BS EN 1992-1-1). The response can be approximately described as a linear load-displacement behaviour, followed by a rapid de-bonding. A further bond enhancement was developed, by inserting oval beads in the rope's core, forming ribbing effect similar to that of reinforcing bars using 10mm diameter Marlow© T12 Technora pre-stressed rope. A 5.5 times enhancement in bond strength was achieved compared to bonded plain fibre.
The use of hierarchical higher-order (HO) approximations (based on the Legendre's polynomials) is an feasible way of implementing p- or hp-refinement to a Finite Element (FE) Model. HO approximations for finite elements are only implemented by adding additional degrees of freedom to the system of equations rather than to the mesh database, resulting in a better computational performance while the order of approximation required is easily modified while keeping linear elements. A simple FEM is presented to explain how HO approximations within interface elements (in such case representing the bond between concrete and ropes) could be used to achieve a better rate of convergence. Consequently, such implementation would be used to derive a cohesive constitutive relation representing the benchmark achieved in the experiments.

Keywords: Fibre Reinforced Concrete; Composite; Bond Strength; Interface Cohesion Elements; Hierarchical Refinement;

1. Introduction

The use of composite materials in construction industry is becoming more popular and sophisticated. Multi-dimensional higher strength composites, optimization of design, material, costs and recyclability are some of the vitally important topics in the evolution of composite engineering. Various environmental conditions (e.g. thermal, chemical, hygral and biological) influence the behaviour and mechanical response of composite materials in various ways. For example, in fibre-reinforced concrete composites, durability is reduced when exposed to alkaline or salty environments [1]. Also, when fibre-reinforced polymers (FRP) embedded in concrete are exposed to elevated temperatures, such as fire loading, differential thermal expansion of the FRP and concrete can take place [2], as well as degradation of commercial epoxy resins. In such situations, the glass transition temperature (GTT), which can be relatively low (not more than 200°C), is often reached, thereby weakening the bond between individual composite fibres, and leading to adhesion loss between the FRP and concrete [1] by up to 80-90% [3, 4].

One way of avoiding such bond loss between fibres and matrix under elevated temperatures, is to avoid using epoxy and enhance the mechanical interaction between individual fibres, using, for example, braided fibres. To increase the bond strength between the reinforcement and concrete, it is possible to use a grid system, where the main tensile reinforcement are bonded with shear reinforcement [5, 6, 7]. Although this system could be effective in ambient conditions, it is unlikely to be suitable under elevated temperatures, were the matrix used to bind the grid system, will eventually melt and consequently the grid system is lost. The system developed in this paper was to create ribs into the rope surface, similar to steel reinforcement, by inserting beads in the core of the rope. This new system is initially investigated by performing

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pull-out experiments at ambient temperature. The bond enhancement from such a system is compared with the bond of plain surface textured rope fibre (later on referred as 'plained rope fibre'). Angle optimization of the braiding is deemed to be fundamental [8]; this was observed by the authors in preliminary tensile testing of carbon and technora fibre ropes.

In this paper, the development of a numerical tool to predict the bond strength for the new system is explained. Computational modelling using interface elements with a cohesive model is a common approach for simulating crack propagations and adopted in this research. A simple cohesive model using a few parameters will be derived to represent the bond behaviour achieved in the experiments. HO approximation in triangular interface elements [9] are used to reduce the need for mesh refinement. Hierarchical HO elements [10, 11] are used in this paper for HO approximation, and their benefits are explained. Various refinements methods will be investigated such as h, p, and hp-refinement.

2. Computational Modelling

In this paper a simple FEM model is presented to explain the implementation of hierarchical HO shape functions in interface elements. Using p, h and hp-refinement, the rate of convergence is examined and potentialities of such technique were reported.

Description of the Investigated Computational Model

A simple model shown in Figure 1 was used, consisting of two tetrahedral with in between prisms representing the interface elements. In CUBIT software, both tetrahedral were tagged with different material values. A C++ program using MOAB Library was built to insert prisms between the two tetrahedral. This was done, by identifying the faces shared between the two different material values and the vertices of such faces were duplicated where a thick-less prisms were inserted.

This model was subject to h-refinement to have 3 different models containing 1, 4 and 16 interface elements between the two tetrahedral respectively. For the purpose of this paper, an external force was applied to one side of the interface element, having a rigid body motion of the solid part, and fixity in all directions on the other side of the model. The interface cohesion behaviour was consider to be linearly. A force of $q(x) = 10.sin(\frac{\pi}{2}.x)$ was applied on the interface element considering the x direction pointing upwards with x=0 located at the bottom of the model. The force function is then applied normally to the interface elements.

Hierarchical Higher Order Shapes Functions

Shape function approximates variables over the finite elements. If such variables do not vary linearly or nearly linear over every element, the best match non-linear approximations and/or best mesh refinement (to linearize the fluctuations of the variables) are required to represent such variations. Appropriate higher order (HO) approximation reduce excessive mesh refinement. A classical HO elements such as 6 noded triangles only achieve quadratic approximation of displacements and linear approximation of stresses. This type of approximation performs best, when used in junction with appropriate mesh refinement, but still gives low rate of convergence with respect to the number of degree of freedoms (dofs) used.

The benefit of using hierarchical HO shapes approximations, is that the degree of approximations can easily be varied to any order and a better rate of convergence is achieved. These HO shape functions are associated with additional dofs, and have only indirect physical meaning of the mesh, and increase relatively depending on the used polynomial order. Although hierarchical HO shape functions were utilised in both 3D volume elements and interface elements, it was necessary to have HO approximation in the interface only, because the solid elements was set as rigid body motion. Convergence rate between h-refinement (mesh refinement of the interface element) and p-refinement are examined. Furthermore, the potential use of localized hp refinement is explained.

Hierarchical shape functions are constructed using Legendre's polynomials and such functions can interpolate displacements over edges, faces and volumes. Full details of the construction of these shape functions is given Ainsworth and Coyle [11]. In this research, an H^1-conforming space is used where shape functions can approximate displacements and forces over the edges and faces. The number of degrees of freedom required for vertex, edge, face and volume for a specific polynomial order p are 1, p-1, (p-2)(p-1)/2 and (p-3)(p-2)(p-1)/6 respectively.

Implementation of Interface Elements in 3D model

Interface elements, which are zero thickness elements, comprising of two triangular faces, that represent crack formation as the element faces separate. The element stiffness in 3-dimensions is represented by considering the normal and two tangential stiffness terms, from which the normal τ_n and tangential τ_1 and τ_2 traction (these components are represented in Figure 2) can be computed.

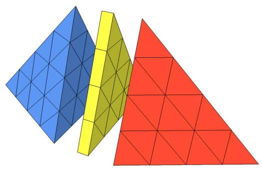

Figure 1: 3D Implementation of Interface Element

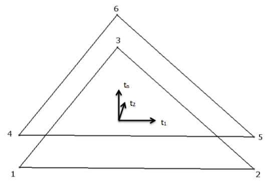

Figure 2: Configuration of Interface Element with zero thickness

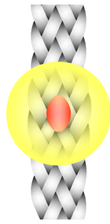

Figure 3: Ribbed Rope Reinforcement using glass beads in the core

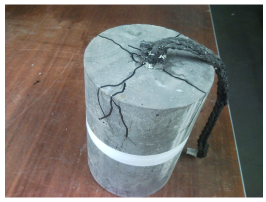

Figure 4: Sample 5TR - Showing rupture of fibre and cracking of concrete

A 3D 4-noded tetrahedral elements were used in the FE model and hence the interface elements were 3-noded triangles. Hierarchical shape functions permitted HO approximations (p-refinement). The formulation for construction of the interface element stiffness matrix and force vector was based on the description given in [9], but mid-side node shape functions were replaced with hierarchical HO shape functions for the edges and faces related to the interface elements. A rotational matrix was constructed to transform the local traction vector and damage matrix to the global coordinates.

Towards the derivation of suitable interface constitutive model

The hierarchical HO approximations for the interface element was implemented in existing software written by the co-author Kaczmarczyk, where HO approximation for the volume were already implemented. This has recently been developed to perform local adaptive hp refinement. Although this paper show a simple model to explain the benefits of hierarchical HO aproximations, a FE model representing the experimental samples, will be investigated using simple cohesive models, using the experimental load-displacement behaviour as a benchmark to achieve a similar behaviour in the numerical model. Hence, the number of parameters represented in the model will be kept to a minimum. Small strains are considered at present, although this a simplification for carbon fibre rope. Under tension, large deformations are likely to occur in all directions.

3. Experimental Investigation

Experimental work was carried out to determine the bond strength of various types of braided fibres ropes and surface textures.

Aim of Investigation

Experimental studies were undertaken to investigate the bond strength between pre-stressed braided fibre ropes and concrete. The first set of experiments were designed to investigate the bond adhesion caused by the surface texture of the braiding while the second and third set of experiments were designed to investigate a novel system developed in this research, to enhance the bond strength of braided fibre ropes. The proposed system is made from braided rope with beads inserted into the core, giving a ribbing effect which can have different pitch lengths. The rope was then pre-stressed to reduce the longitudinal elongation and transverse shrinking of the rope during pull-out. This method was investigated using standard pull-out test conforming with ACI 440.R3-04 [12]. The results of the tests led to a comparison of the bond strength of the proposed approach to that of steel reinforcement and a comparison with plain fibre rope.

Material Description

In the first set of experiments, Siltex© 7mm carbon fibre rope (commercially used as fire insulation) was used. In the second and third set of experiments, 10mm Technora© T12 rope (commercial used for high temperature environments such as fire-rescue and stage performances) provided by Marlow Ropes Ltd (UK) was used. Although T12 are supplied having a PU coating to provide a good abrasion resistance, T12 were used without such coating to perform to avoid the application of polymers. 8mm glass oval beads with a 0.8mm hole through its length where used to create the ribbing effect as shown in Figure 3. Concrete was designed to be C30 (±3MPa), at 28 days. The strength was determined by standard British cube strength rather than ASTM C39.

Sample Description

Six samples were cast for the first set (1-6CP using plain carbon fibre ropes), while another 12 (1-6TP using plain T12 pre-stressed rope and 1-6TR using ribbed T12 pre-stressed rope) were cast for the second (1-6TP) and third set (1-6TR). All samples were manufactured as 150mm diameter and 200mm long cylinders rather than cube shapes as specified in ACI 440.R3-04 [12]. The bond lengths were prepared to be 5 times the diameter of the rope (hence 40 and 50mm for the carbon and technora fibre respectively) and positioned 75mm below the loading surface of the concrete to avoid the compressive region of the loading face. A single glass bead was inserted within the bonded area for samples 1-6TR. The non-bonded area were masked with tape to prevent concrete adhesion. All ropes used were pre-stressed to an average load of 2000N before casting. Six standard cubes were cast from every batch of concrete and used to determine compressive strength after 7 and 28 days of curing. The pull-out samples were cured for 28 days before the pull-out tests were performed.

Testing Procedure

A 250kN Zwick Roell tensile machine was used for the pull-out tests. Every sample was clamped down to the machine bed using a levelled steel plate with a layer of rubber facing the concrete and the end of the rope to the pull-out passed through the plate and anchored to the machine cross-head pin. The loading rate was prescribed to be 1.3mm/min as stated in ACI 440.R3-04 [12]. The distance from the concrete face to the pin centre was measured before testing, while during the testing the cross-head movement and ultimate pull-out force were monitored. After the test, the cylindrical samples were split and the actual bond length and distance of the bond length to the loading surface were measure to determine the bond stress and the elongation of the fibre and strain.

4. Results

Numerical Results

A linear cohesive model was used for the interface elements to show the rate of convergence for a spatially non-linear loading applied to the interface elements.

By varying the mesh size of the models and the Legendre polynomial order, h,p and hp refinement was achieved in the numerical analysis. Sufficient gauss points were necessary to achieve numerical stability. Convergence of results were determined by finding the error difference between the exact and computed displacements. Rate of convergence achieved from the different refinement levels is presented in Figure 5. h-refinement deemed to be unsatisfactory, resulting with a very minimal convergence rate. While p-refinement gave a much better rate of convergence, a combination of both methods gave the best convergence rate.

Using Hierarchical HO approximations, gave a better feasibility when changed from one order to another. This is because, for such system, there was no need of having higher order finite elements. Using linear finite elements, and adding extra dofs with ease to the system of equations, HO approximation was still possible. Such extra dofs, represents 'virtual' nodes on the elements, where their data is not kept on the mesh database, hence give a better computational performance.

Ultimately, better convergence could be achieved by the implementation of localized hp-refinement. Hence, unnecessary higher approximation could be avoided and computational power will only be focused in the crack zone. The ultimate goal was to use hierarchical shape functions for HO approximations, to achieve computational efficiency for a specific level of approximation error.

Experimental Results

Experimental data has be used to determine the intrinsic and overall behaviour of the bond strength of plain carbon and technora fibre rope in comparison with the new ribbed system of technora fibre rope and steel re-bars. Material properties such as concrete strength and mechanical properties of braided fibre were the main contributors to bond strength.

Although ACI 440.R3-04 [12] specifies C30 ± 3 MPa, compressive tests shown from the first set of experiments (samples containing plain carbon fibre) had an average compressive strength of 43 MPa at 34 days, while for the second set (samples containing plain technora fibre) the average strength was 36 MPa and for the ribbed technora fibre samples (third set) the average strength was 40 MPa.

During the first set of experiments, bond strength achieved by the natural surface texture of the braided carbon fibre rope was examined. The first observation was that anchor slippage (due to transverse shrinkage) during pull-out loading which influenced the elongation behaviours in sample 1CP, and mitigated later on for the last 5 samples by fastening the

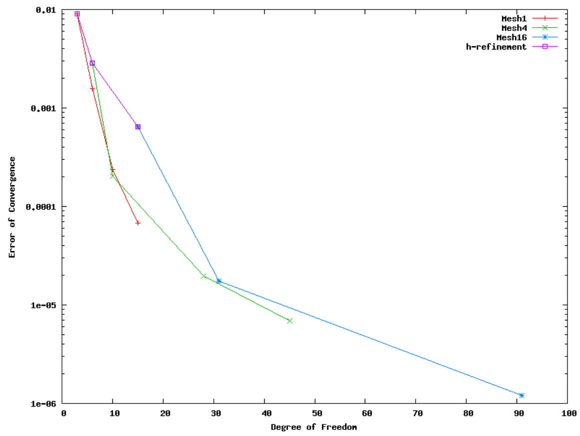

Figure 5: Convergence Results for p & hp refinement

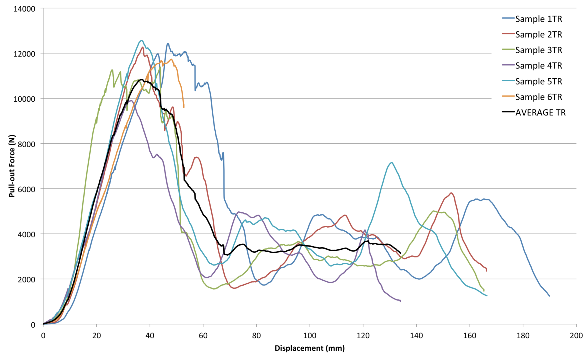

Figure 6: Pull-out Force-Displacement Graph for Ribbed 10mm T12

cables clip at 500 and 1000N of pull-out loading. The fastening caused the fluctuations shown in Figure 8. In 1CP and 4-6CP, bond failure was observed, while 2-3CP, fibre rupture was observed. The initial part of the load-displacement behaviour, where stiffening is observed, is due to the mechanical behaviour of the braiding. Elongation in this part, is due to a combination of strain of the fibre above the bond area and a non-uniform strain along the bond interface. Further on, the load-displacement behaviour was observed to be nearly linear with small stiffness loss half way through the loading in the representative samples 4-6CP. This loss could represent the beginning of the inter-facial bond loss followed by a sharp bond loss. A combination of fibre rupture (few surface carbon fibres have been bonded along with the cement paste) and transversal shrinkage of the fibre cross-section at the interface is thought to be the main contributors for the loss of bond. The overall bond strength was about 36 % (4.9MPa) compared to a 7mm reinforcement steel bar (11.44MPa) as recommended in CEP-FIP Model Code 1990.

The surface texture of the Technora braided fibre ropes used in the second set of experiments are smoother with no superficial deformations due to the nature of braiding, having longer pitch and a different type of weaving. Hence the bond strength was much lower that the first set, having a bumpy behaviour (as shown in graph Figure 7) which was observed in all the six samples (1-6TP). The explanation for this behaviour is linked to the pitch length of the braid. This is nearly equivalent to the distance from one peak to the next, in the load-displacement graph (Figure 7). Hence the adhesion was only due to mechanical abrasion and while no physical fibre bond with cement paste was observed, concrete water content is thought to influence the bond behaviour.

The newly developed system, which consisted of technora fibre rope ribbed with glass beads at the core showed some variations in failure modes. In this third set, all six samples (1-6TR) had similar initial load-displacement (Figure 6) behaviour similar to samples 1-6CP, where initial stiffening followed by linear behaviour can be observed. The failure mode varied from bead crushing to concrete crushing, and some with partial bead and concrete crushing. Fibre rupture between the fibre and concrete was observed driven by high stress concentration and abrasion resistance.

Studies will have to be performed to optimize the pre-stressing load in order to minimize the large strains at the bond interface. The bond strength (7.21MPa) achieved by the third set of experiments was 5.5 times more than that of the second set (1.3MPa), where plain technora fibre was used and 1.66 times more than an equivalent 10mm steel re-bar. The bond strength to weight ratio shows that ribbed techora fibre have 66.15 MPa/kg per unit length of reinforcement compared to 17.63 MPa/kg per unit length for steel rebar (but 4 times more expensive).

5. Conclusions

An effective way of enhancing the bond strength of braided fibre rope has been proposed through the addition beads, resulting in good results compared to the recommended bond strength of steel. Braiding technology as a fibre binder and the use of glass beads to deform the outer surface of the rope are both straightforward to manufacture and the cost of production is reasonable due to omission of resin. Although good bond strength was achieved, rupture and elongation of the rope, means that it is unsuitable at present for use in the construction industry until further development is achieved to mitigate such problems.

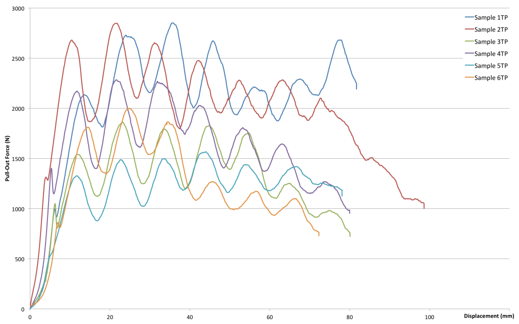

Figure 7: Pull-out Force-Displacement Graph for Plain 10mm T12

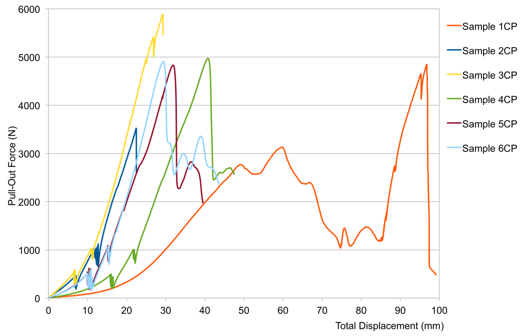

Figure 8: Pull-out Force-Displacement Graph for Plain 7mm Carbon Fibre Rope

The implementation of HO approximations based on hierarchical Legendre polynomials on interface elements in conjunction with a cohesive model, is an excellent method of approximating the complex stress state in the concrete-reinforcement interface, wiht hp-refinement showing good convergence.

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References

[1] F. Ceroni, E. Cosenza, M. Gaetano, M. Pecce, Durability issues of FRP rebars in reinforced concrete members, Cement and Concrete Composites 28 (10) (2006) 857–868.

[2] N. Galati, A. Nanni, L. R. Dharani, F. Focacci, M. A. Aiello, Thermal effects on bond between FRP rebars and concrete, Composites Part A: Applied Science and Manufacturing 37 (8) (2006) 1223–1230.

[3] A. Katz, N. Berman, L. C. Bank, Effect of High Temperature on Bond Strength of FRP Rebars, Journal of Composites for Construction 3 (2) (1999) 73–81.

[4] A. Katz, N. Berman, Modeling the e ect of high temperature on the bond of FRP reinforcing bars to concrete 22 (2000) 433–443.

[5] T. Ohta, R. Djamaluddin, S. Hino, K. Yamaguchi, K. Harada, Flexural properties of concrete beams reinforced with UCAS, Journal of Structural . . . 48A (2002) 1229–1238.

[6] R. Djamaluddin, S. Hino, K. Yamaguchi, Bond capacity of grid system in unresin carbon fiber reinforcement for concrete beams, Journal of Structural Engineering A 50A (2004) 927–934.

[7] S. T. Seo, R. Djamaluddin, Experimental studies on bond capacity of grid system for UCCF cables, KSCE Journal of Civil Engineering 10 (1) (2006) 15–19.

[8] R. Fangueiro, C. Pereira, S. Jalali, M. Araújo, The mechanical properties of braided reinforced composites for application in concrete structures, in: 37th International Symposium on novelties in Textiles, no. June, 2006.

[9] J. Segurado, J. LLorca, A new three-dimensional interface finite element to simulate fracture in composites, International Journal of Solids and Structures 41 (11-12) (2004) 2977–2993.

[10] B. Szabó, I. Babuška, Finite Element Analysis, Wiley Series in Computational Mechanics, John Wiley & Sons, 1991.

[11] M. Ainsworth, J. Coyle, Hierarchic finite element bases on unstructured tetrahedral meshes, International Journal for Numerical Methods in Engineering 58 (14) (2003) 2103–2130.

[12] A. C. I. Committee, ACI 440.3R-04, guide test methods for fiber-reinforced polymers (FRPs) for reinforcing or strengthening concrete structures, Tech. rep., American Concrete Institute (2004).